FLUX ENHANCEMENT OPTIONS FOR AN LEU-FUELED MIT REACTOR

Thomas H. Newton, Jr., Edward E. Pilat, and Mujid S. Kazimi
Nuclear Reactor Laboratory and Nuclear Engineering Department
Massachusetts Institute of Technology
138 Albany St.
Cambridge, MA 02139

ABSTRACT

The Monte-Carlo transport code MCNP was used to evaluate possible arrangements of cores for the MIT Reactor using monolithic LEU fuel. Plate and moderator thicknesses were varied, and fixed absorbers and inner reflectors added in an effort to maximize available neutron fluxes at in-core and ex-core locations of experimental facilities. Addition of D_2O in the H_2O moderator was also evaluated. Comparisons of the fast, epithermal, and thermal fluxes were made at selected locations. Keff was also evaluated and critical blade heights compared with the existing HEU core. Results indicate that the LEU fluxes could approach HEU values with the use of a fueled in-core experimental facility, a fixed boron absorber spider and an inner beryllium reflector.

1. Introduction

The MIT Reactor (MITR-II), currently licensed to operate at 5 MW, contains a hexagonal core that contains twenty-seven fuel positions in three radial rings (A, B, and C), as shown in Figure 1. Typically at least three of these positions are filled with either an in-core experimental facility or a solid aluminum dummy element to reduce power peaking. The remaining positions are filled with standard MITR-II fuel elements. Each rhomboid-shaped fuel element contains fifteen aluminum-clad fuel plates using HEU (93% enriched) in an aluminide cermet matrix with a fuel thickness of 0.76 mm (0.030 in.) and a length of 61 cm (24 inches). The cladding of each fuel plate has 0.25 mm fins to increase heat transfer to the coolant. The fuel has an overall fuel density of 3.7 g/cm^3, with a total loading of 506 g ^{235}U in each fuel element.

The core is light water moderated and cooled and is surrounded by a D_2O reflector. Boron impregnated stainless steel control blades are present at the periphery of the core at each of the sides of the hexagon. In addition, fixed absorbers of boron-stainless steel can be installed in the upper twelve inches of the core in a hexagonal configuration between the inner and second fuel rings as well as in three radial arms extending to the edge of the core.

Several reentrant thimbles are installed inside the D_2O reflector, delivering greater neutron flux to the beam ports outside the core region. Beyond the D_2O reflector, a secondary reflector of graphite exists in which several horizontal and vertical thermal neutron irradiation facilities are present. In addition, the MITR Fission Converter Facility is installed outside the D_2O reflector. This facility contains ten or eleven partially spent MITR fuel elements for a delivery of a beam of primarily epithermal

neutrons to the medical facility for use in Boron Neutron Capture Therapy (BNCT). Figure 2 shows a larger view of the reactor including the reflector regions and experimental facilities.

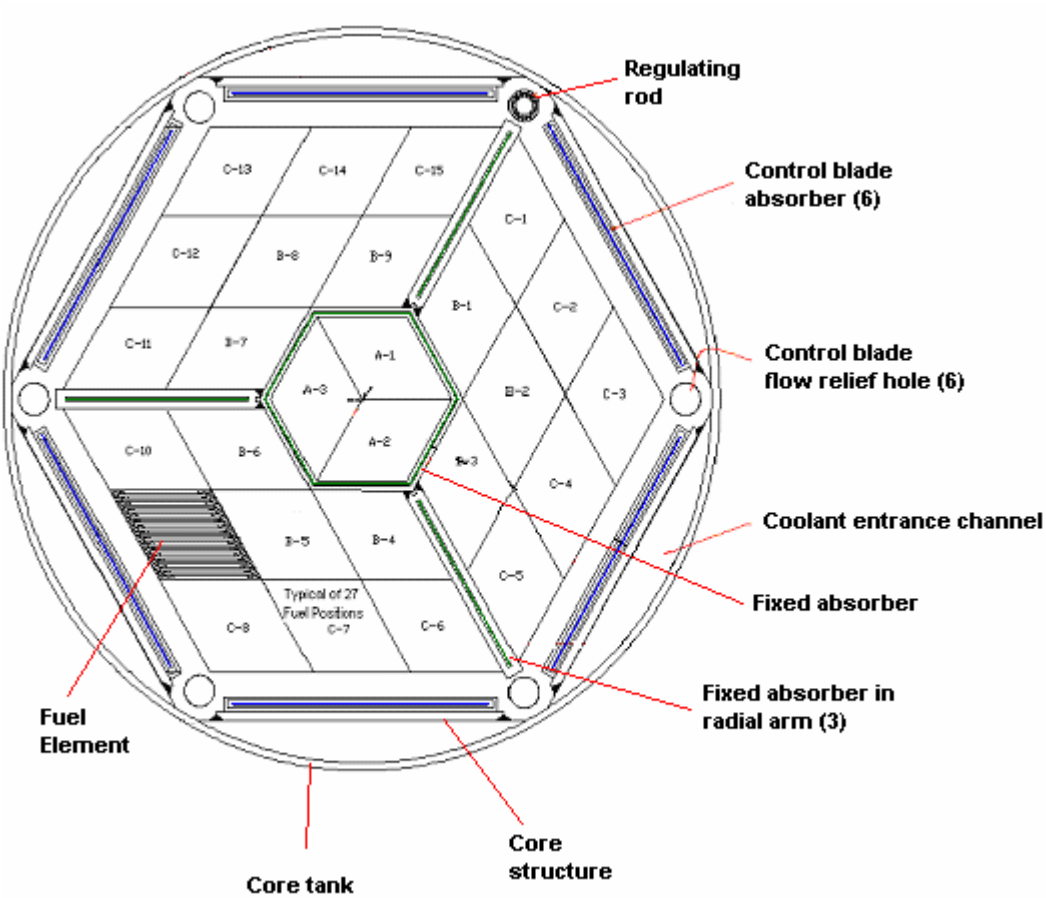

Figure 1. The MITR-II core.

Modeling of the reactor for neutron transport calculations is made using the Monte-Carlo code MCNP. A model of the reactor was first made by Redmond, *et al*. [1]. This model, as well as the MCNP-ORIGEN linkage code MCODE developed by Xu, *et al* [2] was used to more extensively benchmark the HEU core reactivity and burnup for MITR-II core #2. [3]

This model was modified to perform evaluations of possible LEU core configurations. Because conventional LEU dispersion fuels are of insufficient density to maintain criticality for the compact MITR-II core design, monolithic U-Mo fuel with a uranium density of 16.3 g/cm^3 was chosen. Development of this fuel by the RERTR program [4] appears promising. Because of the smoother surface characteristics of the U-Mo fuel, the aluminum cladding was reduced from 0.38 mm as in the HEU case to 0.25 mm. In all

cases, control blades were modeled at 8.5 inches (21.6 cm), the critical height for the reference HEU core.

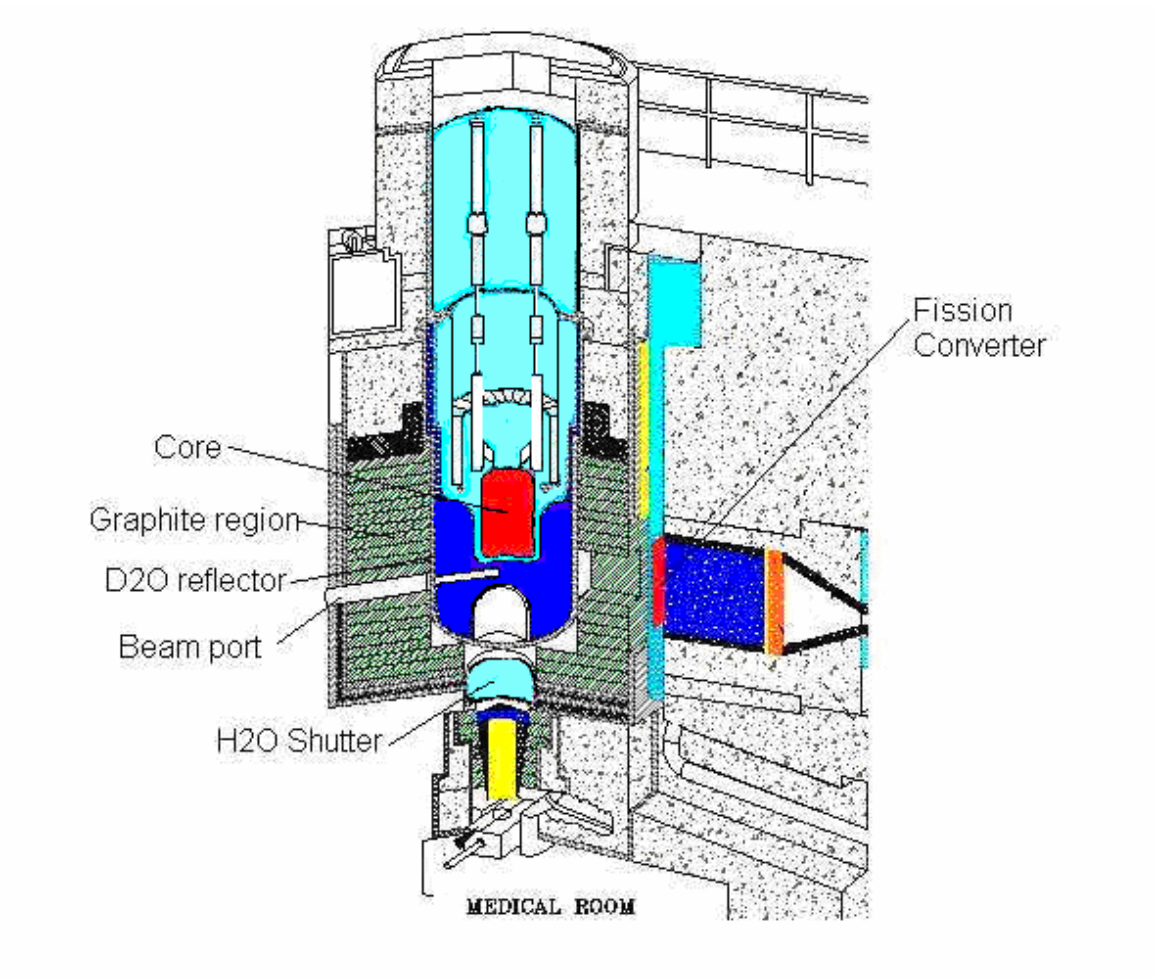

Figure 2. The MIT Reactor

2. Optimization Studies

In order to optimize the choice of fuel configuration, plate number and thickness as well as moderator material was varied to maximize the available neutron flux at in-core and ex-core experimental facilities. The neutron fluxes in five experimental facilities were calculated: An A-ring in-core sample assembly, the twelve inch (30 cm) diameter beam port, the graphite region leading to the fission converter facility for epithermal BNCT, the high-flux pneumatic sample facility (positioned just outside the D_2O reflector opposite a reentrant thimble), and the below core beam line leading to the thermal BNCT facility in the medical room.

In addition to fluxes, K_{eff} was also determined. Burnup studies using MCODE suggest that an initial K_{eff} of at least 0.993 for an LEU core will equal the approximate core lifetime of the current HEU core.

Merely changing the fuel-moderator ratio for an LEU core while keeping the overall core geometry the same as the reference HEU core did not significantly improve experimental fluxes, so other options were proposed, including core configuration changes. These include use of absorbing materials in different locations of the fixed absorber spider, the use of a beryllium inner reflector, and the use of an LEU fueled liner for the in-core sample assembly.

Overall, approximately two hundred separate fuel, moderator, and core configurations were analyzed.

3. Moderator Variations

Because of the increased amount of absorption in-core with the addition of U-238 in LEU fuel, other options to reduce in-core absorption were considered. Addition of D_2O in the primary coolant system was studied. Figure 3 shows K_{eff} vs. number of plates per element in core. The pure H_2O case clearly shows an effect of increasing K_{eff} with an increase in fuel mass. However, the addition of as little as 20% D_2O adds significantly more negative reactivity because of further undermoderation of the reactor due to the increased diffusion length of D_2O.

Figure 4 shows the effect on the thermal neutron flux in the twelve inch (30.5 cm) diameter beam port (12SH1). In all cases, other ex-core experimental facilities showed similar trends. Variations in the number of plates for a given moderator composition has little effect on the flux. Use of LEU fuel with pure H_2O moderation in a similar configuration to the HEU core results in about a 20% drop in neutron flux. Addition of D_2O increases this flux, with the HEU core equivalent flux being reached at 25% D_2O.

The use of D_2O has disadvantages, however. There could be considerable difficulty in maintaining a constant H_2O/D_2O ratio during operation. In addition, a sudden insertion of H_2O from a leak or emergency cooling action could result in a significant reactivity insertion. Also, the buildup of tritium in the primary system could make in-core maintenance and refueling operations more difficult. Because of these issues, the addition of D_2O was not considered immediately practical.

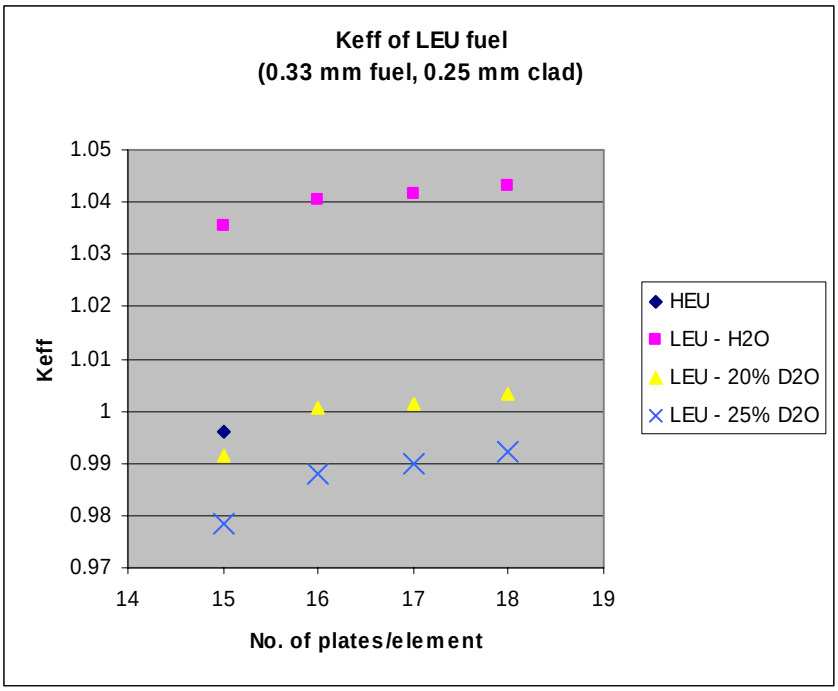

Figure 3. K_{eff} of H_2O and D_2O cores

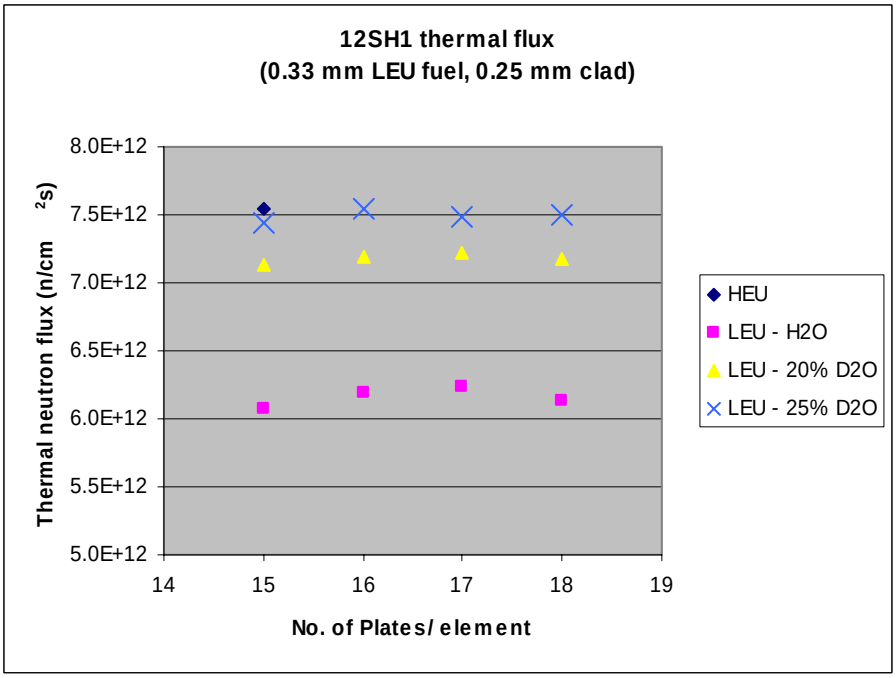

Figure 4. 12SH1 thermal flux in H_2O and D_2O cores

4. Internal Reflector

Since the present HEU core uses aluminum dummy elements to reduce peaking and provide space for in-core experiments, it was decided to replace the aluminum with an internal beryllium reflector to reduce absorption. Figure 5 shows one such configuration in which the A-ring elements are replaced by beryllium and a central irradiation facility. The fuel elements are reduced to half size, with two half-elements in each C-ring position. Each B-ring position contains one half-element with solid beryllium adjacent to the A-ring. Hafnium absorbers were placed in the fixed absorber spider positions in order to enhance the flux delivered to the ex-core facilities.

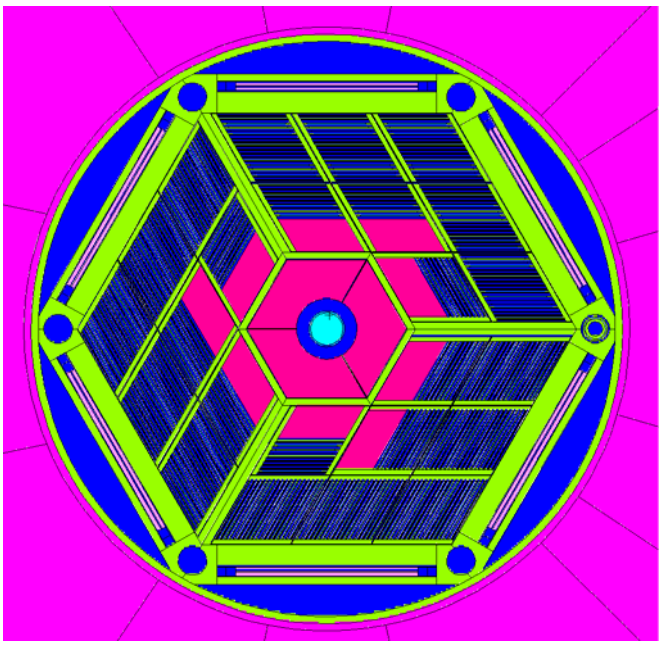

Figure 5. MCNP model of LEU core with Be internal reflector

Fuel-to-moderator ratios were varied by changing the fuel thickness and number of plates in this configuration. The thickness of the plates were varied from 0.25 mm to 0.84 mm. Figure 6 shows the effect of this variation on K_{eff}. Because of the increased absorption by the fixed hafnium absorbers and the reduction of number of fuel elements, it was difficult to attain criticality at the reference control blade position. The use of fewer plates per element resulted in a higher K_{eff}. However, the use of fewer plates also resulted in a lower thermal neutron flux to experimental facilities, as can be seen in Figure 7. Elements with eight plates per half-element had fluxes approaching the HEU fluxes, while larger number of plates actually exceeded the HEU fluxes.

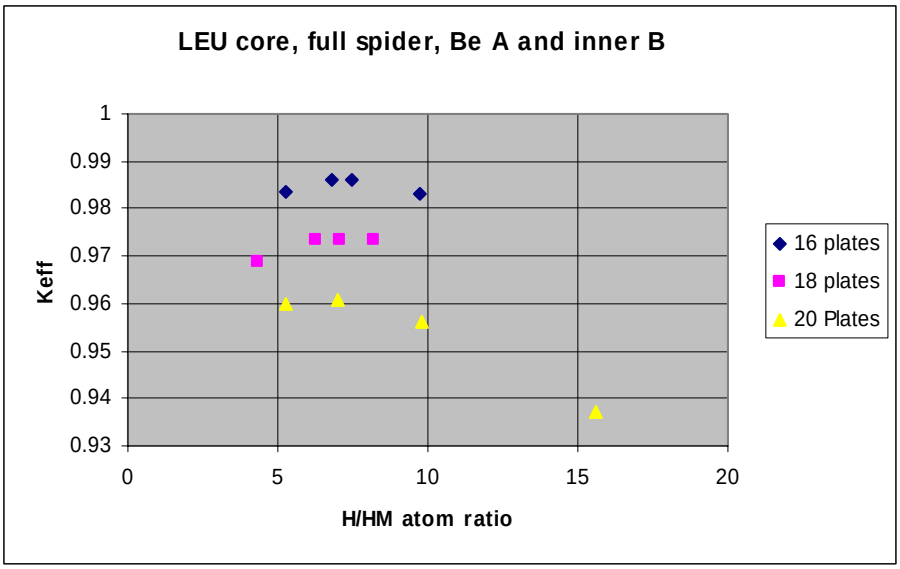

Figure 6. K_{eff} of LEU cores with interior Be reflector and fixed absorber

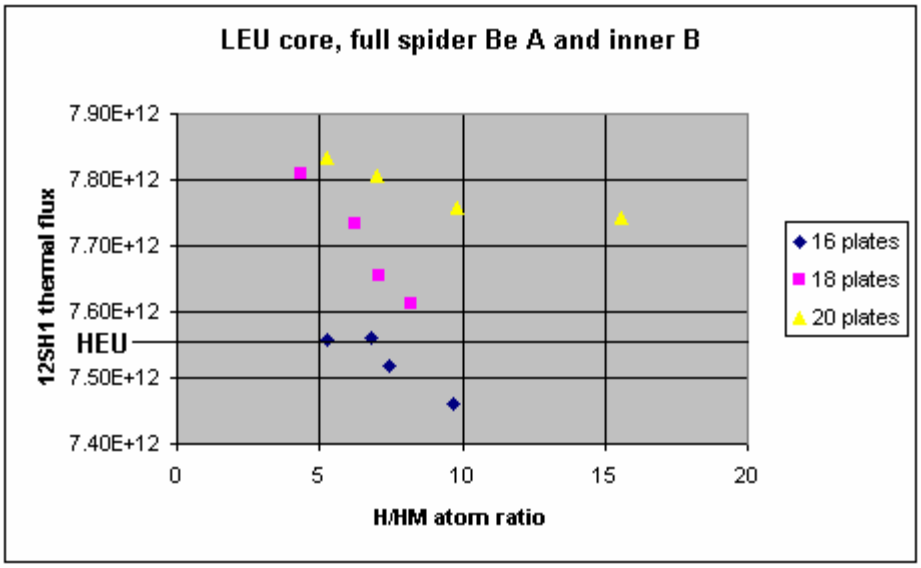

Figure7. 12SH1 Neutron flux of LEU cores with interior Be reflector and fixed absorber

One of the drawbacks to the use of an inner beryllium reflector is the peaking of power in the fuel adjacent to the beryllium. Figure 8 shows the local-to-average power ratio in each fuel position and the maximum peaking in an individual fuel plate for a nine half-element core with beryllium inner reflector. The elements adjacent to the Be reflector show significantly higher peaking than those radially further out in the former C ring positions. The values here show similar element peaking as that in the reference HEU core, which has a maximum element peaking of 1.23. However, the plate peaking is

significantly higher as compared with the HEU value of 1.39. It should be noted that plate peaking values in the outer positions are dependent on the orientation of the plates with respect to the core. From these results, it is clear that neutron absorbers will have to be configured so as to locally reduce peaking.

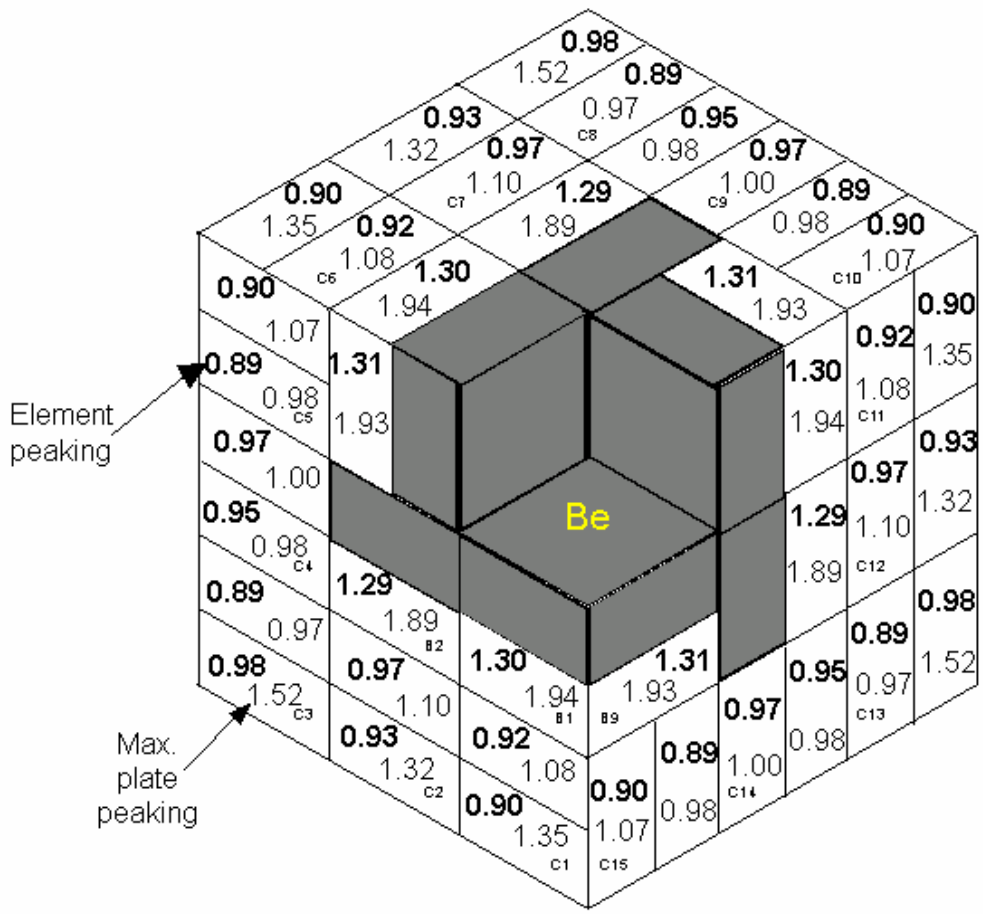

Figure 8. Peaking in LEU core design

5. In-Core Facility

A number of options were studied to enhance the fluxes available in-core. Selected results from this are presented in Table 1. In-core thermal (<0.4 eV) and fast (>3 keV) fluxes are shown, as well as K_{eff} and the ratio of thermal fluxes present in the twelve inch beam port as compared with the HEU reference core (7.5E12 n/cm^2 s at the tally point). Enhancement of the fast flux in the in-core facility is the goal of the inner core design, since the majority of experiments irradiated in-core requires fast neutrons. The only method found to be effective in significantly enhancing the fast flux is to surround the experiment with LEU fuel.

Six cases are shown in Table 1. The two HEU cases are of the reference core with the in-core facility surrounded by a 1.6 mm annulus of either water or aluminum. The effect or the material on thermal and fast flux can be easily seen. The four LEU cases chosen are one with LEU in the HEU reference configuration (including thicker fuel and

cladding), and three other cases of the nine plate half-element design presented above with inner beryllium reflector. Of the three latter cases, the in-core sample assembly is centered in the core and surrounded by a 1.6 mm annulus of LEU monolithic fuel (beryllium in the unfueled case). Two fueled in-core facility cases are presented, one with boron impregnated stainless steel in all fixed absorber positions and one with hafnium in only the radial absorber position in the B-ring in an attempt to reduce the B-ring power peaking mentioned above.

These results show that design of an in-core facility with a thermal flux equivalent to the HEU reference core is fairly easily accomplished, as demonstrated with the unfueled (Be annulus) case where the in-core thermal flux is actually enhanced by about 20%. Enhancement of the fast flux, however, is more difficult, as can be seen with the remaining two fueled in-core facility cases. Such enhancement, when possible, comes at the expense of the flux at the ex-core facilities or available reactivity.

Although it is recognized that technology does not exist to shape an annular configuration of monolithic fuel, it is believed that this geometry is sufficient for optimization studies such as this. More realistic shapes are now being studied.

One disadvantage to using fuel surrounding the in-core facility is that of power peaking. These studies show that the power produced by the fuel surrounding the central irradiation facility can be over twice that of the highest power producing fuel plate in other element positions. Options to adequately cool this fuel or reduce the power produced without significantly reducing the experimental fast flux are being studied.

Spider configuration and material	**In-core annulus material**		**K_{eff}**	**Thermal Flux (<0.4 eV) n/cm^2 s**	**Fast Flux (>3 KeV) n/cm^2 s**	**Ex-core Thermal Flux Ratio to HEU**
water	water	HEU, water annulus	0.9960	1.07E+14	1.57E+14	1.00
water	Al	HEU, Al annulus	0.9960	4.31E+13	1.85E+14	1.00
water	Al	LEU in HEU configuration	0.9816	8.06E+13	1.51E+14	0.93
full--boron SS	Be	LEU, half-element design	0.9856	1.27E+14	7.98E+13	1.00
full--boron SS	fuel	LEU, half-element design	0.9976	2.58E+13	1.67E+14	0.97
Hf B arm only	fuel	LEU, half-element design	1.0108	3.31E+13	1.90E+14	0.93

Table 1. In-core facility results

6. Conclusions

This study has primarily focused on the neutronics of potential LEU core designs on the assumption that monolithic U-Mo fuel will be certified. This will, of course, depend on the certification of materials irradiation performance and manufacturing to needed tolerances by the RERTR program at ANL.

A number of options for an LEU fueled MIT reactor have been studied, including promising designs using mixed H_2O/D_2O moderator or using an inner beryllium reflector. The mixed moderator design, although promising from a flux point of view, has limitations with reactivity and operational concerns. The inner beryllium reflector design appears to be more feasible and can, under some circumstances, deliver fluxes needed to experimental facilities. Issues with power peaking, both near the reflector and in a possible fueled annulus, will need to be solved to assure adequate cooling in all areas.

Although it is possible to design cores with higher reactivity, greater ex-core thermal flux, and greater in-core facility fast flux, no design has yet been identified to accomplish all three simultaneously. It is evident that sufficient operational flexibility must be designed into an LEU MIT reactor so that flux enhancement options for immediate experimental needs can be easily implemented. It only by safely meeting the needs of the scientific community that conversion of all research reactors to LEU can be fully accepted.

References

1. E. Redmond, J. Yanch, and O. Harling, "Monte Carlo Simulation of the MIT Research Reactor," *Nuclear Technology*, **106**, pp. 1-14 (1994).

2. Z. Xu, P. Hejzlar, M. Driscoll, and M. Kazimi, "An Improved MCNP-ORIGEN Depletion Program (MCODE) and its Verification for High-Burnup Applications," PHYSOR, Seoul, Korea, Oct. 2002.

3. T. Newton, Jr., Z. Xu, E. Pilat, and M. Kazimi, "Modeling the MIT Reactor Neutronics for LEU Conversion Studies," PHYSOR-2004, Chicago, IL, April, 2004.

4. C.R. Clark, G.C. Knighton, M.K. Meyer, and G.L. Hoffman, "Monolithic Fuel Plate Development at Argonne National Laboratory," Proceedings of the 2003 International Meeting on Reduced Enrichment for Research and Test Reactors, Chicago, IL October, 2003. ANL/NE/TM03-05.